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(54) **Method for improved color reproduction.**

(57) An improved method is disclosed for using a linear mixing space, such as a CIE color space, to determine the quantities of coloring agents needed to reproduce a color, applicable for example to printing a color which matches an original color on a CRT display. The calculations match hue, saturation and reflectance so that the matching color appears like the original color and so that characteristics of an original image are preserved. An original color's definition is converted into coordinates in the linear mixing space. An achromatic region (42) in the linear mixing space, preferably elliptically shaped, is defined to include the coordinates of the neutral coloring agents. Original colors falling within the achromatic region (42) are matched with quantities of neutral coloring agents only. For original colors falling outside the achromatic region, the coordinates of a pure hue approximating the hue of the original color is then determined in the linear mixing space from the coordinates of selected primaries. A saturation ratio is determined which approximates the saturation of the original color. The saturation ratio is used to calculate the quantities of coloring agents which will produce a matching color. A reflectance for the matching color is determined from a function which maps the saturation ratio to a reflectance curve for the primary coloring agents. A quantity of a neutral coloring agent is then determined from the matching color's reflectance.

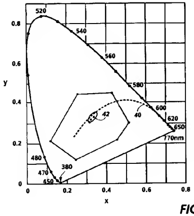

FIG. 3A

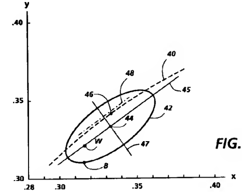

FIG. 3B

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The present invention relates generally to digital color reproduction, and, in particular, to a color reproduction method for accurately producing a color in a subtractive color printing system which represents an original color.

Conventional color CRT displays and color television monitors are self-luminous, light-emitting color rendering devices which use an "additive" coloring system. An additive coloring system may be composed of red, green, and blue (RGB) phosphor signals, referred to as the primary coloring agents (or primary colorants or primary colors) of the system, which combine to form each color of a color image. Such an additive color rendering system is considered to be a linear system because any color producible by the additive system is the sum of the independent primary colorant intensities of the system.

Digital color printers, color copiers, color electrostatic plotters, and similar printing devices are non-self-luminous, light-absorbing and reflective color rendering devices and produce color according to a subtractive color process by applying the primary coloring agents (i.e., the dyes, inks, toners, or pigments) to a white medium (or a transparent medium if back-lit). Light is reflected from the surface on which the color appears and the combination of the light-absorbing coloring agents used "subtract" colors from the source illumination by canceling bands of wavelengths to provide the proper color. Colors displayed on a device using a subtractive color system are comprised of certain amounts of cyan, magenta, and yellow (CMY) primary coloring agents (or primary colorants or primary colors).Application of no coloring agents produces white, and the device's white color is the white substrate (paper) on which the primary coloring agents are laid down. Application of all coloring agents produce black. The subtractive color reproduction system is nonlinear.

All of the colors physically producible by a color reproduction device is called the "gamut" of the device. The gamuts of additive and subtractive color reproduction devices do not correspond to one another because the devices produce color according to different physical methods. Reproducing a color's appearance accurately or appropriately for a particular situation requires selecting the color in the output system's device gamut which most accurately reproduces the appearance of the color as specified in the input system's device gamut.

Accurate and appropriate color reproduction between devices utilizing different color reproduction technology is aided by a device independent representation of color where an input image color is matched to an appropriate output gamut color in a color specification format that is independent of both the input and output primary coloring agent specifications. One such colorimetric, device independent color specification conforms to an internationally standardized color notation system established by the Commission Internationale de l'Eclairage (the "CIE"). The CIE standard assigns numeric tristimulus values, denoted X, Y, and Z, to describe colors according to their appearance under standard sources of illumination as viewed by a standard observer.

Color correction methods used to map colors from an additive color system's gamut to a subtractive color system's gamut generally use look up tables, matrices, or mathematical transformations for mapping an input image color to its colorimetric color specification and then to an appropriate matching output color, expressed in subtractive primary coloring agent quantities, in the gamut of the subtractive color reproduction device. These methods generally require the measurement of large numbers of colorimetrically measured color patches produced by the subtractive color reproduction device for representing the output color gamut. See, for example, Hung et. al., U.S. Patent 4,959,711, entitled "Method and Apparatus for Correcting the Color of a Printed Image"; and E'Errico, U.S. Patent 4,941,039, entitled "Color Image Reproduction Apparatus Having a Least Squares Look-Up Table Augmented by Smoothing". These techniques, which require matrices or tables which depend on the color of each primary coloring agent, need to be recalculated whenever a primary coloring agent changes.

U.S. Patent No. 4,751,535, issued to Myers and assigned to Xerox Corporation, the same assignee herein, provides a technique for matching a color which does not require colorimetric measurement of a large number of color patches, and which uses a device independent, linear mixing space, such as a CIE color space, in which to produce an appropriate matching color. The complete specification of the color matched printing method of U.S. Patent No. 4,751,535 may be found in the disclosure thereof which is hereby incorporated by reference. The method disclosed therein for determining quantities of the primary coloring agents to be used to generate a matching color begins with the step of colorimetrically measuring the linear mixing coordinates of the primary and secondary coloring agents, black, and the white of the substrate (paper) to obtain each color's x, y chromaticity coordinates (or chromaticities) in the CIE color space known as the 1931 Chromaticity Diagram, and the color's luminance, or reflectance value, Y. Next the original color's coordinates, usually expressed as additive RGB coordinates are converted to linear mixing coordinates using known conversion techniques.

Then, the original color is matched to quantities of subtractive primary and secondary coloring agents in a hexagonally shaped output device gamut. The gamut is defined by the two-dimensional x, y chromaticity coordinates of the six primary and secondary measured coloring agents of the output device, plotted in the 1931 Chromaticity Diagram, and is divided into six mixing triangles by a center point inside the hexagon. An original color falling into one of the mixing triangles will be matched by quantities of the primary and secondary coloring agents at the vertices and a quantity of a neutral or achromatic (either white or black) coloring agent. The mixing triangle used for color matching is selected based on the coordinates of the center point and of the original color, using a vector cross-product technique and calculation described in detail in U.S.P. 4,751,535 at col. 12. The coordinates of a pure hue" are found by projecting a line from the center point of the selected mixing triangle through the original color to intersect a side of the triangle. The intersection point defines the pure hue, undiluted with neutral coloring agents, which matches the hue of the original color. Calculation of the pure hue permits calculation of the quantities of the two primary and the neutral coloring agents which will approximate the hue, saturation and reflectance of the original color in the device gamut.

A second, triangular shaped linear mixing plane is then used to adjust the saturation and reflectance of the pure hue in order to obtain the matching color. The original color may either be inside this second mixing triangle, if the original color is inside the gamut of the subtractive color reproduction device, or outside the second mixing triangle, if the original color is outside the gamut of the device. Within this second mixing plane, the pure hue is adjusted in all three dimensions from a line of constant reflectance equal to that of the pure hue to the line of constant reflectance equal to that of the original color. If the original color falls outside the triangle, the matching color is the most saturated available color on that line, but if the original color is in the triangle, the technique also adjusts the saturation of the matching color to that of the original color. Finally, the quantities of the coloring agents needed to match the original color are determined from the primary amounts and from the reflectance and saturation adjustments previously calculated.

The color matching technique disclosed in U.S.P. 4,751,535 is very effective because it is based on the discovery of a computational technique which accurately determines coloring agent quantities directly from the definition of the original color. However, the technique has been found to produce inappropriately matching colors when matching low chroma or nearly achromatic colors. For those colors, unpredictable and undesirable shifts in hue may occur which also may affect the method's ability to produce a balanced and smoothly changing gray scale of achromatic colors. In addition, the printing of standard test patterns of color patches involving uniformly changing colored squares from one CMY primary to another shows the tendency for the method to unpredictably produce under-saturated colors with too much black.

The color matching technique disclosed in U.S.P. 4,751,535 is preferably implemented by supplying in a coded, unchangeable format, the linear mixing coordinates of the colorimetrically measured CMY, RGB, black, and white colors produced by a particular device on a particular substrate under certain manufacturer controlled environmental conditions. The method implemented in this manner produced inaccurately matching colors when a substrate or coloring agent was used in the device which varied from the manufacturer's standards. In such an implementation, there is no ability for the user to tailor the device's color reproduction performance to meet the type of substrate (paper), coloring agent, or environmental condition actually being used.

An object of the present invention is to provide an improved method for reproducing an original color using a linear mixing space.

Accordingly, the present invention provides a method for reproducing an original color using a linear mixing space, the method being as claimed in any one of the appended claims.

The invention described herein is a modification to the color matching method disclosed by Myers in U.S.P. 4,751,535. Such an improved color reproduction method makes use of novel techniques for defining an achromatic mixing region to be used in determining the quantities of coloring agents needed to match an original color, and for determining the reflectance value for the matching color, thereby overcoming the deficiencies in U.S.P. 4,751,535 noted above. In addition, the method provides for user input of colorimetrically measured linear mixing coordinates for the actual subtractive device coloring agents and substrate being used under actual production conditions.

In one embodiment the method comprises the steps of selecting at least two primary coloring agents from at least three coloring agents whose linear mixing coordinates define a polygon, the coordinates of the at least two coloring agents defining vertices at ends of a side of the polygon, and defining an achromatic region in the polygon containing linear mixing coordinates of at least two neutral coloring agents. Preferably, the achromatic region is an ellipse having a center point at defined by the linear mixing coordinates coordinates of an equal energy stimulus, and having a semi major axis oriented in the linear mixing space

substantially parallel to a line tangential to a curve defined by the linear mixing coordinates of a plurality of reference illuminants (also called Planckian radiators), the tangential line being tangent to a point on the curve equal to the coordinates of the equal energy stimulus. The achromatic region defines a region where the primary coloring agent quantities will be zero, and only neutral coloring agents, specifically the black coloring agent, will produce a matching color.

Then, a line is projected from the center point's coordinates through linear mixing coordinates of the original color to intersect the boundary of the achromatic region and the side of the polygon. Linear mixing calculations are performed with the original color's linear mixing coordinates and the linear mixing coordinates of the at least two primary coloring agents and of at least one neutral coloring agent to determine quantities of the coloring agents to be used to generate a color approximating the original color. The linear mixing calculations comprise calculating relative quantities of the selected primary coloring agents based on lengths of parts of the side of the polygon; and calculating relative quantities of a mixture of the selected primary coloring agents and of a neutral coloring agent based on the portion of the projecting line which lies outside the achromatic region. Then, a pattern which closely approximates the determined quantity of each coloring agent is selected and the coloring agents are applied in the selected pattern to produce the matching color.

In another aspect of the present invention, the reflectance value for a color matching an original color is determined in a novel way according to an equation developed through empirical testing which maps a previously calculated saturation ratio to a reflectance curve. This matching color reflectance value is then used to determine the amount of a neutral coloring agent to be applied to produce a matching color. In particular, the matching color reflectance value is used to determine the amount of black coloring agent to apply.

The present invention will be described further, by way of examples, with reference to the accompanying drawings, in which:-

Figure 1 is a flowchart of the general steps of an improved color matched printing method according to an embodiment of the present invention;

Figure 2 is a flowchart illustrating in greater detail the operation of block 20 in Figure 1 for obtaining valid measured coloring agents according to the embodiment of the present invention;

Figures 3A, and 3B are graphs of the CIE linear mixing plane showing the achromatic region used to determine quantities of coloring agents according to an embodiment of the present invention;

Figure 4 is a flowchart illustrating in greater detail the steps of box 80 in FIG. 1, for creating the achromatic and mixing regions shown in Figures 3A, 3B and 6;

Figure 5 is a flowchart illustrating in greater detail the steps of box 22 in FIG. 1, for converting the definition of the original color to coordinates in a linear mixing space;

Figure 6 is a graph of the CIE linear mixing plane showing the achromatic and polygonal mixing regions used to determine quantities of coloring agents according to an embodiment of the present invention;

Figure 7 is a flowchart which illustrates in greater detail the operation of block 110 in Figure 1 for adjusting saturation; and

Figure 8 is a graph mapping a range of saturation ratios to a reflectance curve for determining reflectance of the matching color according to the present invention.

Figure 1 shows one technique according to an embodiment of the present invention for determining coloring agent quantities making use of linear mixing in the CIE Chromaticity Diagram color space. The technique of this embodiment begins with colorimetrically measuring and storing, in box 20, the linear mixing coordinates of the coloring agents which will be used to generate the matching image. Although the coordinates could be in any appropriate color space, they are preferably the coordinates of each coloring agent in a linear mixing color space such as the CIE 1931 Chromaticity Diagram, which makes use of each coloring agent's CIE x, y, Y coordinates. It is important to obtain accurate, actual colorimetric measurements of the linear mixing coordinates with a spectrophotometer or colorimeter. These measurements include the CIE x, y, Y coordinates of each of the primary (CMY) and secondary (RGB) coloring agents which will be applied, the CIE x, y, Y coordinates of the black color produced either by the superimposition of C, M, and Y, or from the black coloring agent, and the CIE x, y, Y coordinates of the substrate (paper) which serves as the reference white. Rather than measure the linear mixing coordinates of the coloring agents each time an image is generated, the coordinates of a representative sample of each coloring agent may be measured and stored in advance, provided the variation about the measured values is relatively small.

Accurate and appropriate color reproduction is also affected by many different coloring agent and environmental factors that would not be provided for in all cases by advance colorimetric measurement of the necessary coloring agents, even if those measurements are highly accurate. Such factors include whether color changes occur in the coloring agents being used to produce the matching color, changes in

the application characteristics of the coloring agents, such as changes in the viscosity of a toner, changes in the equipment used to apply the coloring agents, whether a printer, plotter, CRT or other equipment, changes in the surface characteristics of the substrate to which the coloring agents are applied, and color changes resulting from changes in temperature, humidity, paper or other causes. A satisfactory method for color reproduction must accommodate such coloring agent and environmental changes.

Therefore, in one embodiment of the measuring step of box 20, several combinations of coloring agents and substrates are measured and these linear mixing coordinates are made available for selection by the user of the method to most closely define the conditions under which color reproduction will be performed. In addition, there is provided a mechanism for the user of the method to specify his or her own measurements for a specific combination of coloring agents and substrates, when the conditions under which color reproduction will be performed are not available for selection.

FIG. 2 illustrates the substeps of the measuring step of box 20 to accommodate the user's definition of the conditions under which color reproduction will be performed. The measuring step of box 20 provides the method of the embodiment with the proper set of measured primary, secondary, black, and white coloring agent coordinates to be used for reproducing an original color. In box 60, a query is made, in any conventional manner for detecting a user-supplied input, to determine if the user of the method will be supplying a set of measured coloring agent coordinates. If the query is negative, the previously measured and stored coloring agent coordinates for a particular set of coloring agents on a specific substrate are obtained, in box 62, for use in the remaining steps of the method. If the query is positive, the user-supplied measured coordinates are obtained, in box 64.

Next, in boxes 66 and 68 conventional error checking techniques are used on the coloring agent coordinates received from the user to ensure as much as possible that the coordinates have been correctly entered and are valid for the device gamut. These error checking techniques may include verifying that the measured primary and secondary coloring agent coordinates logically make the desired mixing triangles when plotted in the Chromaticity Diagram, using conventional line segment intersection and point - line segment position algorithms to calculate whether a vector line segment drawn from the first color to the next color in a sorted order is to the left of a particular centrally located point, such as the point known as the "equal energy white" or the "equal energy stimulus" point of the Chromaticity Diagram.

The next step in the method shown in FIG. 1 is to define, in box 80, an achromatic color area within the gamut of the subtractive color reproduction device and to define the mixing regions to be used for color matching in subsequent steps of the method. The method of the present invention defines an achromatic region on the Chromaticity Diagram such that for any original color falling within the achromatic region, only a quantity of a neutral coloring agent need be determined to match the original color. For an original color falling outside the achromatic region, the substeps for adjusting the saturation and reflectance, in boxes 110 and 140, from information about the pure hue found in box 30, involve determining where the original color is in relationship to the achromatic region boundary.

There is illustrated in FIGS. 3A and 3B the achromatic region 42 located in the Chromaticity Diagram relative to black body curve 40. Black body curve 40, also called the Planckian locus, is a plot of chromaticity points of Planckian radiators at different temperatures (K). The points represent the color stimuli produced by these Planckian radiators (ideal furnaces or full radiators) maintained at ideal temperatures, as given on the absolute temperature scale in kelvin (K). FIG. 3A shows achromatic region 42 plotted within the hexagonal device gamut which will be used to create the mixing triangles for mixing the primary and neutral coloring agents needed to match an original color. FIG. 3B shows a detailed portion of the Chromaticity Diagram where achromatic region 42 is plotted in relationship to black body curve 40. In the illustrated embodiment, the achromatic region found to be most suitable for improving color reproduction was an elliptically shaped region.

FIG. 4 illustrates the steps for creating an elliptically shaped achromatic region 42 and will be discussed in relation to region 42 of FIG. 3B. The method illustrated in FIG. 4 uses conventional and known mathematical techniques for defining, representing, and manipulating ellipse structures. In box 82 of FIG. 4, the center point for the ellipse is established, preferably at point 44 which represents the chromaticity coordinates of the equal energy stimulus, as defined by the CIE, at $x = 0.333334$ and $y = 0.3333330$. Next, in box 84, the orientation of the ellipse in the Chromaticity Diagram is determined by finding the slope of the ellipse's semi-major axis 45 (FIG. 3B), the longer axis of ellipse 42, which is established as approximately parallel to black body curve 40 by drawing a line passing through center 44 with slope equal to the slope of a line 48 tangent to black body curve 40 at point 46. Point 46 is the point on black body curve 40 with the same x chromaticity as the equal energy stimulus ($x = 0.333334$).

Next, in box 86 of FIG. 4, an ellipse is defined from certain initial constraints. In the implemented embodiment, the achromatic ellipse starts as a minimally sized ellipse centered at the equally energy

stimulus and capable of including within or on its boundary an arbitrary approximately neutral color defined at chromaticity coordinates, $x = 0.33100$, $y = 0.33000$. To accomplish this, the semi-major axis 45 of the ellipse is computed to be equal to 0.00488695 and the semi-minor axis 47 is computed to be equal to 0.00191228. It is preferable to maintain as constant the ratio of the ellipse's semi-major diameter to its semi-minor diameter. In the implemented embodiment, the ellipse's semi-major axis 45 is approximately four times the size of its semi-minor axis 47. The two foci of this initial ellipse are then found to be at x, y chromaticity points (0.336860,0.336125) and (0.329818,0.330530), respectively.

The final size of the achromatic ellipse is determined to be the smallest ellipse needed to include both the measured reference white (substrate) and black coloring agents of the subtractive color reproduction device for which colors are being matched, labeled W and B respectively on FIG. 3B. The steps in boxes 88,90,92, and 94 accomplish this. It is preferable to increase the size of the ellipse in small increments while maintaining the preferred, approximate four-to-one size ratio of the major and minor axes. Then, in box 96, these dimensions may be stored for later use in determining the saturation adjustment ratio step in box 110 of FIG.1.

Conceptually, once defined by the steps in boxes 82 through 96 of FIG. 4, the elliptically shaped region remains a fixed, achromatic region at all reflectance values in the three-dimensional linear color mixing space. An original color with chromaticities falling within or on the boundary of the achromatic region at any reflectance level will be reproduced as an achromatic color, thereby eliminating the problems with the earlier method of hue shifts occurring for original colors with low chromas, and of hue shifts occurring for original colors with certain reflectance values.

The color mixing regions of the linear mixing plane are defined next, in box 98. The mixing regions are created as one set of fixed mixing triangles. Each triangle has as its base one side of the hexagon, with one of its base vertices being at the x, y coordinates of one of the subtractive CMY primaries and the other at the x, y coordinates of one of the subtractive RGB primaries. The third vertex of each color mixing triangle is the measured, reference white of the substrate (paper). Since the coordinates of each mixing triangle are known, the dimensions of each triangle may be computed and stored once, in box 98, for all subsequent calculations needed to perform color mixing.

The next step in the method illustrated in FIG. 1 is to receive the definition of the original color, in box 22, and convert that definition to linear mixing coordinates in the same color space as those measured and stored in box 20. FIG. 5 shows the operational steps for implementing the step in box 22. The proper conversion technique for converting the original color's coordinates is selected in box 102. For additional accuracy in the illustrated embodiment of the method of the present invention, several conversion methods (transformations) are provided to accommodate RGB color specifications produced from different sources. If it is known, for example, that a particular additive device utilizing NTSC standard primaries produced the original color, it is preferable to select the transformation technique which specifically transforms the RGB color specification to CIE tristimulus values with respect to the particular phosphors which created the original color, and with respect to the reference white of the particular additive device.

In box 106, a test is made to determine whether the original color is achromatic. Making this determination now provides a short cut in the method. If the original color is achromatic, the amount of neutral (black) coloring agent may be directly calculated, in box 108. The test for determining whether the original color is achromatic is simply to determine whether the chromaticity coordinates of the original color, x_o, y_o, are inside achromatic region 42 (FIG. 3B). The details of this mathematical determination depend on the type of achromatic region 42 defined. In the illustrated embodiment, achromatic region 42 is an ellipse and the determination is accomplished mathematically using conventional techniques for testing whether a point is inside or on the boundary of an ellipse.

The amount of neutral (black) coloring agent, determined in box 108, is determined to be equal to 1 - the reflectance (Y_o) of the original color. The quantities of the other primary coloring agents are set to zero, and the method then proceeds directly to box 36 for selection of the pattern for producing the matching color, since the steps in boxes 24, 28, 30, 110, 140, and 34 of FIG. 1, for determining the quantities of the primary coloring agents, are not necessary.

Once the original color's coordinates have been converted into appropriate linear mixing coordinates, the luminance, or reflectance value Y, of the original color is then adjusted, in box 24 of FIG. 1, for out-of-bounds reflectance values, which occur when an original color is lower in reflectance than the measured black coloring agent or higher in reflectance than the measured paper white. This is accomplished in the same manner as in the known color matching method of U.S. Patent 4,751,535.

The next step in the improved color reproduction method of FIG. 1 is to find the pure hue for an original color, in box 30. The pure hue is a color of the same hue as the original color which can be generated without any neutral coloring agents. In other words, the pure hue falls on the linear mixing line between two

of the primary coloring agents, within one of the mixing triangles, as shown in FIG. 6. The pure hue is found by determining the relative quantities of the two selected primaries which generate it, based on the position of an intersection point along the linear mixing line.

Determining the pure hue involves first finding the two primary coloring agents, in box 28, which designate the mixing triangle to be used. The two primary coloring agents may be selected using a vector cross-product technique in the same manner as described in detail in U.S.P. 4,751,535 at col. 12 line 56. The coordinates of the primary and secondary coloring agents and the center point defining the three vertices for each mixing triangle are fixed coordinates, previously defined in box 80 of FIG. 1. FIG. 6 shows the primary color pair defining the vertices of one mixing triangle, designated as Primary1 and Primary2, respectively. The third vertex of each mixing triangle is the measured reference white coloring agent, at coordinates x_w, y_w, labeled W.

The x,y coordinates of the pure hue, x_p,y_p, in the two-dimensional linear mixing plane of FIG. 6 are determined next, in box 30 of FIG. 1. The pure hue, designated PURE, is at the intersection of a line projecting from center white point W through the original color with the line which makes up the side of the selected mixing triangle connecting two primary coloring agents. The primary coloring agents, Primary1 and Primary2, at the end points of the intersected side always include one of the CMY primary coloring agents and one of the RGB secondary coloring agents. These coloring agents are "mixed" in relative quantities to obtain the pure hue according to the relationship between the lengths of the parts, P1 and P2, into which the line of the intersected side is divided. As used herein, "mixing" refers to the mixing of two or more coloring agents in adjacent areas of a pattern, with negligible superimposition. It will be understood that the dots or other areas of the pattern which contain distinct coloring agents must be small enough to be below the resolution limit of the human eye, so that the pattern is perceived as having a single color. In particular, the relative quantities of Primary1 and Primary2 have the same ratio as the lengths of the parts P1 and P2 of the linear mixing line bounded by those primaries. Thus, the coordinates of the pure hue are needed to find the lengths of the parts, P1 and P2 and to determine the relative quantities of Primary1 and Primary2. The coordinates, x_p, y_p, of the pure hue are determined in the same manner as described in U.S. Patent 4,751,535, using line slope equations. Then, the relative quantities P1 and P2 of Primary1 and Primary2 respectively are determined from the coordinates of the pure hue, x_p, y_p, according to Equations (1), (2), and (3):

$$\frac{\text{Qty of Primary1}}{\text{Qty of Primary2}} = \frac{\text{P1}}{\text{P2}} \tag{1}$$

$$\text{P1} = \frac{[(x_{primary2} - x_p)^2 + (y_{primary2} - y_p)^2]^{0.5}}{[(x_{primary1} - x_{primary2})^2 + (y_{primary1} - y_{primary2})^2]^{0.5}} \tag{2}$$

and

P2 = 1-P1 (3)

It can be seen that the line segments P1 and P2 are proportional to the Primary quantities. When the pure hue at x_p, y_p is equal to Primary1, 100% of Primary1, represented by line segment P1 extending from Primary2, and 0% of Primary2, represented by line segment P2 extending from Primary1, are needed to formulate the pure hue. Similarly, as the pure hue approaches Primary2 along the linear mixing line, the amount of Primary1 decreases from 100% as line segment P1 gets shorter, and the amount of Primary2 increases from 0% as the line segment P2 gets longer.

The present invention provides for adjusting saturation, in box 110 of FIG. 1, without regard to the reflectance of the original color, and with respect to the saturation range available in the mixing triangle that is outside the achromatic region. This saturation adjustment, which will be designated SR, is fundamentally a ratio of the original color's hue to the pure hue, and is based on the premise that, for each portion of the subtractive color reproduction device gamut at any reflectance level, there is an achromatic range that affects the permissible saturation range for the matching color. Depending on the particular gamut and on

the shape of the achromatic region, this achromatic range may be a unique region for each portion of the gamut defined by a mixing region, as shown in FIG. 6.

The implementation of the step 110 recognizes that a ratio of the original hue to the pure hue calculated for adjusting saturation should not include the portion of the distance representing the hue that is inside the achromatic region. That distance is represented as dotted line segment 56 in FIG. 6. An original color falling within the achromatic region along line segment 56 will be reproduced as an achromatic color, with no quantities of the primary CMY coloring agents applied at all. It follows from this that the saturation for a color matching an original color falling along line segment 58 should be determined along a range extending only from some minimally saturated color, at the boundary of achromatic region 42, at point x_e,y_e, where line segment 58 intersects with achromatic region 42, to the most saturated color available in the gamut, at the x_p,y_p coordinates of the PURE color. Thus, the saturation adjustment ratio in the present invention scales the saturation of the original color to a saturation between a minimum saturation outside the achromatic region and the maximum saturation at the pure hue.

The flowchart of FIG. 7 illustrates the steps in implementing the saturation adjustment concept illustrated geometrically in FIG. 6. First, there is calculated, in box 112, the coordinates of the boundary intersection point, x_e,y_e, of achromatic region 42 with the line projecting from the reference white through the original color to the pure hue, denoted x_p, y_p.The details of this calculation depend on how achromatic region 42 is designated. Since, in the illustrated implementation, achromatic region 42 is an ellipse, finding boundary point x_e,y_e involves conventional mathematical techniques for determining the equation for line 58, solving simultaneous equations for the two intersections of line 58 with ellipse 42, and finding the proper intersection point as the one closest to the coordinates of the original color.

Once the coordinates of the boundary intersection point, x_e,y_e have been determined, the distance from the boundary to the pure hue, designated as $A_{e/p}$ and from the boundary to the original color, designated as $A_{e/o}$ may be easily determined, in box 114, using equations (4) and (5) below:

$$A_{e/p} = \{(x_p - x_e)^2 + (y_p - y_e)^2\}^{0.5} \qquad (4)$$

$$A_{e/o} = \{(x_o - x_e)^2 + (y_o - y_e)^2\}^{0.5} \qquad (5)$$

The next step, in box 116, involves determining the minimal primary coloring agent quantity for the selected primary pair, Primary1 and Primary2. A color matching an original color located just beyond the boundary of achromatic region 42 will have the minimal saturation available for the saturation range permissible, and will be accurately reproduced by applying only a small quantity of the primary coloring agents. This quantity, however, depends on the particular primary pair, and thus should be reflected in the calculation of the saturation ratio. The minimal primary coloring agent quantity for the selected primary pair, Primary1 and Primary2, designated as AMTMIN is computed as follows,

$$\mathrm{AMTMIN} = \frac{A_{e/p} * \mathrm{MINDEN}}{1 - \mathrm{MINDEN}} \qquad (6)$$

where the quantity MINDEN is an average of the two lowest area coverages available for the first primary of a particular primary pair, and * denotes multiplication. The minimum area coverages are available from the area coverage table utilized in later steps to select the patterns to apply to achieve the proper primary coloring agent quantities to reproduce a matching color. In particular, the index into the area coverage table for the minimum area coverage available for Primary1 should be identified, and used to retrieve the appropriate minimum coverage. Then, the next lowest minimum coverage may be retrieved, and the two minimum coverages averaged together to produce the MINDEN quantity. Preferably, the quantities MINDEN and 1 - MINDEN are determined and stored for each primary pair once to minimize access to the area coverage table.

Next, in box 118, the saturation adjustment ratio, SR is computed from Equation (7):

$$\mathrm{SR} = \frac{A_{e/o} + \mathrm{AMTMIN}}{A_{e/p} + \mathrm{AMTMIN}} \qquad (7)$$

In boxes 120 and 122, the saturation adjustment ratio is clipped to 1.0.

The method then continues with the step of determining the reflectance in box 140 of FIG. 1. The reflectance for the matching color, designated Y_m, is determined from a reflectance curve representing the mapping of the range of saturation ratios available to a curve of reflectance values for the primary coloring agents. FIG. 8 illustrates graph 130 for such a reflectance curve. The x axis of graph 130 contains the range of saturation ratios (SR from Equation (7)) available, beginning with a saturation ratio near zero to the right of dotted line 132 which represents the boundary of achromatic region 42 (FIG. 6), and extending to the maximum saturation of 1.0 at point 134. The y axis of graph 130 represents the range of available reflectance values, from Y_b, the reflectance for the black coloring agent, to Y_w, the reflectance for the reference white substrate (paper). For a given saturation ratio, SR, a point on the reflectance curve corresponds to the reflectance of the matching color, Y_m. The function used to map the saturation ratios to the reflectance curve to produce the reflectance for the matching color, Y_m, has been discovered through empirical methods, and is given by the following equation:

$$Y_m = \{Y_w^{(1.0-SR^{10(Y_o - Y_p)})}\} * \{Y_p^{SR}\} \qquad (8)$$

and,

$Y_m = 1.0$ if $Y_m > 1.0$ (9)

where

Y_o is the reflectance of the original color;

Y_p is the reflectance of the pure hue, calculated as follows:

$Y_p = P1Y_{primary1} + P2Y_{primary2}$ (10)

SR is the saturation ratio found for the matching color in Equation (7) above; and

*denotes multiplication.

Returning now to FIG. 1, once the reflectance for the matching color, Y_m, has been determined, the quantities of the coloring agents needed to match the original color may be determined, in box 34 of FIG. 1. The coloring agent quantities to be calculated are those of the black coloring agent, denoted as a_b, and the two primary coloring agents which mix to provide the pure hue. The quantity of black coloring agent can be directly calculated, using the results of Equations (8) and (9). The quantity of black is the quantity which will be added to the coloring agent mixture applied to produce the matching color. If the reflectance of the original color, designated Y_o, is greater than the computed reflectance of the matching color, Y_m, then the amount of black coloring agent, a_b, is set to zero, and no black is added to produce the matching color. For all other cases, however, a_b is computed as follows:

$Y_{o/range} = (Y_o * (Y_w - Y_b)) + Y_b$ (11)

where $Y_{o/range}$ is a modified reflectance value for the original color, based on its position in the total range of available reflectances from Y_b to Y_w, and,

$$a_b = \frac{(Y_m - Y_{o/range})}{(Y_m - Y_b)} \qquad (12)$$

The quantities of the primary coloring agents are determined in a manner similar to the known color matching method of U.S. Patent 4,751,535. The quantities of the primary coloring agents must take into account the selection of the primary color pair in box 28, since the total quantity of the pure hue is made up of a subtractive CMY primary and an adjacent subtractive RGB primary, which is actually generated from two of the subtractive CMY primaries. One CMY primary will be present throughout the pure hue areas,

while the other CMY primary will be superimposed with the first primary only in the RGB primary areas. The relative amounts of each CMY primary depend in which mixing triangle the original color falls. Table 1 summarizes how to determine the quantities of CMY primaries according to the new ratios of pure hue to original hue, and pure hue reflectance to original hue reflectance. The total quantity of the pure hue, a_p, used in Table 1 is equal to the saturation adjustment ratio, SR in Equation (7) above, the P1 and P2 quantities used in Table 1 are the quantities determined in box 30 (FIG. 1), using equations (2) and (3) above, and the symbol * denotes multiplication.

TABLE 1

Mixing Triangle		Quantity of Cyan	Quantity of Magenta	Quantity of Yellow
Primary1	Primary2			
Cyan	Green	a_p	0	$P2^*a_p$
Green	Yellow	$P1^*a_p$	0	a_p
Yellow	Red	0	$P2^*a_p$	a_p
Red	Magenta	0	a_p	$P1^*a_p$
Magenta	Blue	$P2^*a_p$	a_p	0
Blue	Cyan	a_p	$P1^*a_p$	0

In box 36 of FIG. 1, an area coverage pattern is selected which will best approximate the coverage provided by the quantities of the two primary and the neutral coloring agents. This pattern is selected in the same manner as described in U.S.P. 4,751,535.

The technique of the present invention is equally applicable to color matching problems utilizing other color specification systems. For example, instead of RGB color coordinates, HLS or LUV coordinates could be received and converted into coordinates in a linear mixing color space from which coloring agent quantities could then be determined. Colors printed on an electrostatic printer could be matched to thermally printed colors, and printed colors could be matched on a CRT display.

Claims

1. A method for reproducing an original color using a linear mixing space, including performing linear mixing calculations in the linear mixing space with linear mixing coordinates of the original color and linear mixing coordinates of at least two primary coloring agents and with linear mixing coordinates of at least one neutral coloring agent to determine quantities of the coloring agents to be used to generate a color approximating the original color; characterised in that the linear mixing calculations include calculations based on a positional relationship in the linear mixing space between the original color and an achromatic region (42) defined in the linear mixing space.

2. A method according to claim 1, characterised in that the achromatic region (42) is an elliptically shaped region containing linear mixing coordinates of at least two neutral coloring agents; having a center point (44) defined by linear mixing coordinates of an equal energy stimulus; and having a semi major axis oriented in the linear mixing space substantially parallel to a line (48) tangential to a curve (40) defined by linear mixing coordinates of a plurality of Planckian radiators, the tangential line (48) being tangent to a point on the curve (40) approximately equal to one of the linear mixing coordinates of the equal energy stimulus.

3. A method according to claim 2, characterised in that the size of the elliptically shaped achromatic region (42) is defined by a constant proportional relationship between the semi major axis and a semi minor axis.

4. A method according to claim 3, characterised in that the constant proportional relationship is a ratio of approximately four to one.

5. A method according to any one of claims 1 to 4, characterised by

   selecting the at least two primary coloring agents from at least three primary coloring agents, the at least three primary coloring agents having linear mixing coordinates which define a polygon in the

linear mixing space;

selecting linear mixing coordinates of a center point within the polygon; and wherein

the step of selecting the at least two primary coloring agents includes selecting two of the at least three primary coloring agents whose coordinates define vertices at ends of a side of the polygon which intersects a line projecting from the center point's coordinates through the original color's linear mixing coordinates;

the achromatic region (42) is inside the polygon; and

when the linear mixing coordinates of the original color are outside the achromatic region, the step of performing linear mixing calculations to determine the quantities of the coloring agents to be used to generate the approximated color includes

calculating relative quantities of the selected primary coloring agents based on lengths of parts of the side of the polygon;

calculating a saturation adjustment ratio based on lengths of parts of the projecting line which are outside the achromatic region, for adjusting the relative quantities of the selected primary coloring agents to determine the quantities of the primary coloring agents to be used to generate the approximated color; and

calculating the quantity of the at least one neutral coloring agent based on a calculated reflectance for the approximated color.

6. A method according to claim 5, characterised in that the step of calculating the saturation adjustment ration further includes scaling the saturation adjustment ratio from a minimum nonzero saturation adjustment quantity representing the saturation adjustment ratio for an original color closely positioned to the achromatic region (42) on the projecting line, to a maximum saturation adjustment quantity representing the saturation adjustment ratio for an original color positioned on the projecting line at or outside the side of the polygon.

7. A method according to claim 5 or 6, characterised in that the substep of calculating the quantity of the neutral coloring agent includes

calculating a reflectance coordinate for the approximated color according to a reflectance curve function which relates the saturation adjustment ratio to a range of reflectance values for the approximated color; and

using the calculated reflectance coordinate, a reflectance coordinate for the original color, and a reflectance coordinate for the neutral coloring agent to determine the quantity of the neutral coloring agent.

8. A method according to any one of claims 5 to 7, characterised in that the step of performing linear mixing calculations further includes applying a saturation accelerator factor to the quantities of primary coloring agents to be used to generate the approximated color, so that, when an original image contains highly saturated original colors, the approximated color will be mapped into a compressed high saturation range of colors with our approximated colors similarly generated.

9. A method according to any one of claims 1 to 4, characterised by

one of the linear mixing coordinates of the original color is a reflectance coordinate defining a reflectance value of the original color; and

when the linear mixing coordinates of the original color are inside the achromatic region, the step of performing linear mixing calculations further includes

determining the quantities of the at least two primary coloring agents to be zero; and

calculating a quantity of the at least one neutral coloring agent based on the reflectance value of the original color.

10. A method according to any one of claims 1 to 4, characterised in that

the achromatic region is a maximum size sufficient to contain linear mixing coordinates of at least two neutral coloring agents; and

the step of performing linear mixing calculations in the linear mixing space includes

performing two-dimensional linear mixing with the original color's linear mixing coordinates and with the linear mixing coordinates of the primary coloring agents to obtain linear mixing coordinates of a hue approximating that of the original color; and

performing two-dimensional linear mixing with the linear mixing coordinates of the hue and of the

original color, and with linear mixing coordinates of a point on the boundary of the achromatic region, to determine a saturation adjustment ratio quantity to adjust the hue to obtain the approximated color; the point on the boundary of the achromatic region being an intersection point of the boundary of the achromatic region with a line projecting from the linear mixing coordinates of one of the at least two neutral coloring agents through the original color's linear mixing coordinates.

11. A method according to claim 10, characterised in that the step of performing linear mixing calculations in the linear mixing space further includes performing linear mixing with a reflectance coordinate of the hue, with a reflectance coordinate of the original color, and with a reflectance coordinate of the at least one neutral coloring agent to determine a neutral coloring agent quantity to adjust the hue to obtain the approximated color.

12. A method according to claim 11, characterised in that the substep of performing linear mixing with reflectance coordinates includes determining a reflectance coordinate for the approximated color according to a reflectance curve function which relates the saturation adjustment ratio quantity to a range of reflectance values for the approximated color.

13. A method according to claim 11 or 12, characterised in that the substep of performing linear mixing with reflectance coordinates includes determining a reflectance coordinate, Y_m, for the approximated color according to the equation,

$$Y_m = \{Y_w^{(1.0-SR^{10(Y_0-Y_p)})}\}*\{Y_p^{SR}\}$$

where

Y_0 is the reflectance coordinate of the original color;
Y_p is the reflectance coordinate of the hue;
Y_w is the reflectance coordinate of the neutral coloring agent;
SR is the saturation adjustment ratio quantity; and
* denotes multiplication.

14. A method for reproducing an original color using a linear mixing space to determine quantities of primary coloring agents and at least one neutral coloring agent to be used to generate a color approximating the original color, the method including

determining quantities of original coloring agents which generate an original color;

determining linear mixing coordinates of the original color in the linear mixing space based on the quantities of original coloring agents;

defining a polygon in the linear mixing space using linear mixing coordinates of at least three primary coloring agents;

selecting linear mixing coordinates of a center point within the polygon;

selecting, from the at least three primary coloring agents, at least two primary coloring agents whose coordinates define vertices at ends of a side of the polygon which intersects a line projecting from the center point's coordinates through the original color's linear mixing coordinates;

defining an achromatic region (42) in the polygon having a maximum size sufficient to contain linear mixing coordinates of at least two neutral coloring agents;

calculating the quantities of the selected primary coloring agents and the at least one neutral coloring agent according to the positional relationship in the linear mixing space between the original color and the achromatic region;

storing an area coverage value for each of a set of available coloring agent patterns;

selecting a pattern which closely approximates the calculated quantity of each coloring agent; and

applying the coloring agents in the pattern to reproduce the original color.

15. A method according to claim 14, characterised in that the calculating step includes

calculating relative quantities of the selected primary coloring agents based on lengths of parts of the side of the polygon intersected by the projecting line;

calculating a saturation adjustment ratio based on lengths of parts of the projecting line which are

outside the achromatic region, for adjusting the relative quantities of the selected primary coloring agents to determine the quantities of primary coloring agents;

calculating a reflectance coordinate for the approximated color according to a reflectance curve function which relates the saturation adjustment ratio to a range of reflectance values for the approximated color; and

calculating the quantity of the neutral coloring agent using the calculated reflectance coordinate, a reflectance coordinate for the original color, and a reflectance coordinate for the neutral coloring agent.

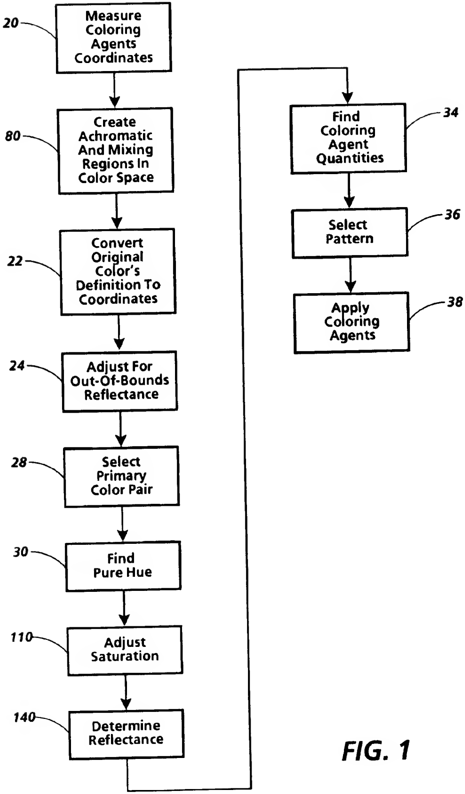
20
Measure Coloring Agents Coordinates
80
Create Achromatic And Mixing Regions In Color Space
22
Convert Original Color's Definition To Coordinates
24
Adjust For Out-Of-Bounds Reflectance
28
Select Primary Color Pair
30
Find Pure Hue
110
Adjust Saturation
140
Determine Reflectance
34
Find Coloring Agent Quantities
36
Select Pattern
38
Apply Coloring Agents

FIG. 1

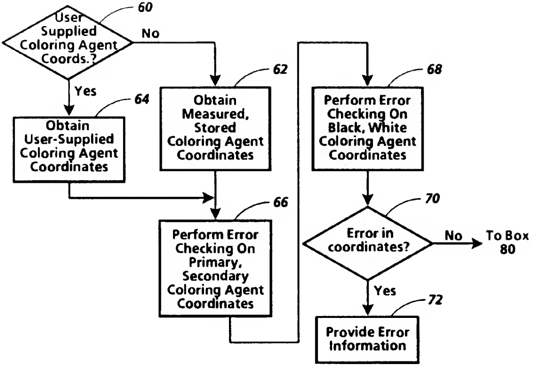
60
User Supplied Coloring Agent Coords.?
No
Yes
62
Obtain Measured, Stored Coloring Agent Coordinates
64
Obtain User-Supplied Coloring Agent Coordinates
66
Perform Error Checking On Primary, Secondary Coloring Agent Coordinates
68
Perform Error Checking On Black, White Coloring Agent Coordinates
70
Error in coordinates?
No
To Box 80
Yes
72
Provide Error Information

FIG. 2

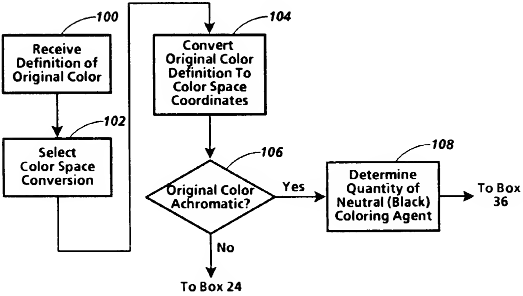
100
Receive Definition of Original Color
102
Select Color Space Conversion
104
Convert Original Color Definition To Color Space Coordinates
106
Original Color Achromatic?
Yes
No
To Box 24
108
Determine Quantity of Neutral (Black) Coloring Agent
To Box 36

FIG. 5

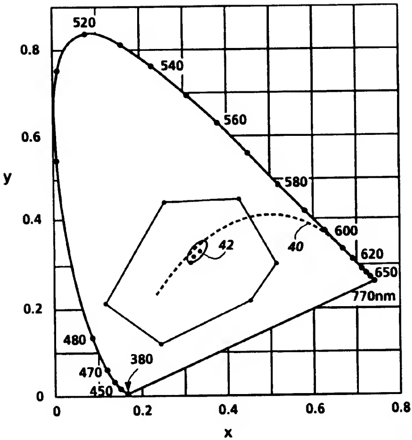
520
540
560
580
600
620
650
770nm
480
470
450
380
42
40
0.8
0.6
0.4
0.2
0
y
0
0.2
0.4
0.6
0.8
x

FIG. 3A

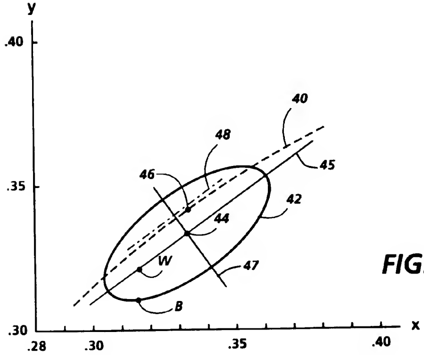
y
.40
.35
.30
40
48
45
46
42
44
W
47
B
.28
.30
.35
.40
x

FIG. 3B

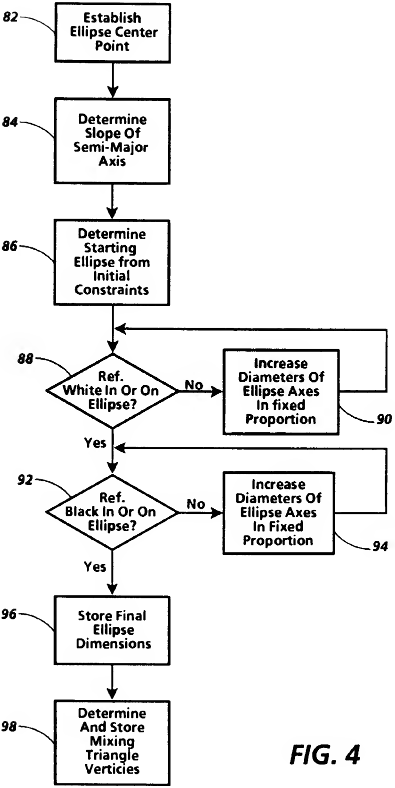
82
Establish Ellipse Center Point
84
Determine Slope Of Semi-Major Axis
86
Determine Starting Ellipse from Initial Constraints
88
Ref. White In Or On Ellipse?
No
Increase Diameters Of Ellipse Axes In fixed Proportion
90
Yes
92
Ref. Black In Or On Ellipse?
No
Increase Diameters Of Ellipse Axes In Fixed Proportion
94
Yes
96
Store Final Ellipse Dimensions
98
Determine And Store Mixing Triangle Verticies

FIG. 4

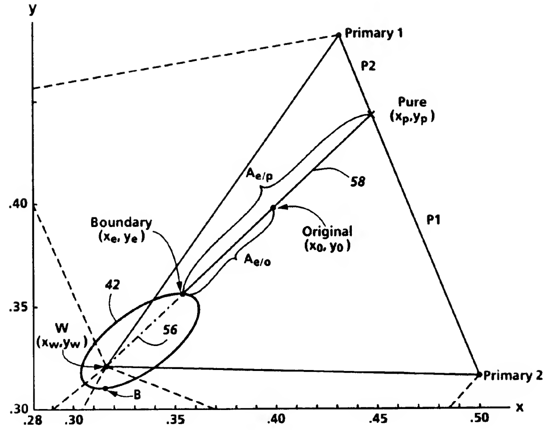
y
Primary 1
P2
Pure
(x_p, y_p)
$A_{e/p}$
58
.40
Boundary
(x_e, y_e)
Original
(x_o, y_o)
P1
$A_{e/o}$
42
.35
W
(x_w, y_w)
56
Primary 2
B
.30
.28
.30
.35
.40
.45
.50
x

FIG. 6

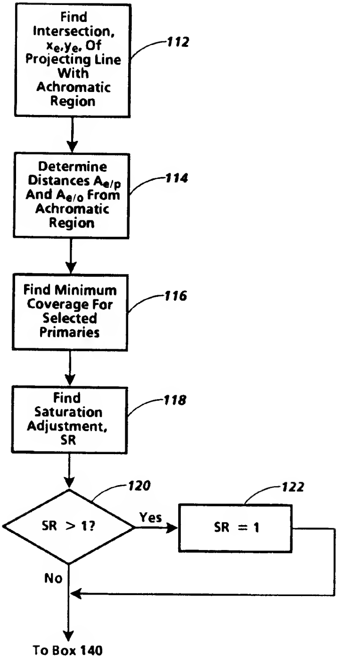
Find Intersection, x_e, y_e, Of Projecting Line With Achromatic Region
112
Determine Distances $A_{e/p}$ And $A_{e/o}$ From Achromatic Region
114
Find Minimum Coverage For Selected Primaries
116
Find Saturation Adjustment, SR
118
120
SR > 1?
Yes
122
SR = 1
No
To Box 140

FIG. 7

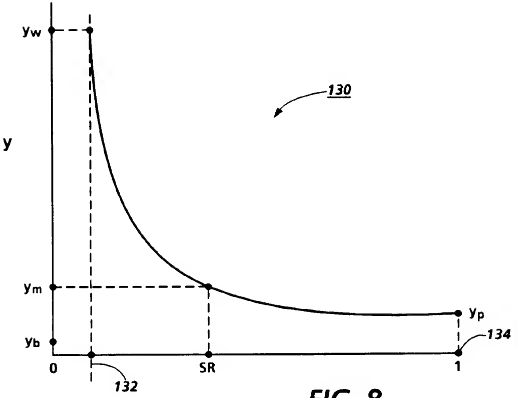

FIG. 8

European Patent Office

EUROPEAN SEARCH REPORT

Application Number

EP 92 31 1463

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.5)
D,A	EP-A-0 264 281 (XEROX) * abstract; figures 3-11 * * page 6, line 9 - page 11, line 43 *	1-15	H04N1/46
A	EP-A-0 454 275 (AGFA) * abstract; figures 1,2 *	1,14	
A	US-A-4 985 759 (ITO) * abstract; figures 1-5,17 * * column 5, line 14 - column 6, line 68 *	1,2,5,9,10,14,15	
A	US-A-4 758 885 (SASAKI ET AL.) * abstract; figures 1-11 * * column 2, line 40 - column 4, line 60 *	1,14	
A	COMPUTEE GRAPHICS vol. 12, no. 3, 1978, ALVY RAY SMITH 'color gamut transfrom pairs'		

TECHNICAL FIELDS SEARCHED (Int. Cl.5)

H04N

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	08 MARCH 1993	KASSOW H.

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
O : non-written disclosure
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T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons

& : member of the same patent family, corresponding document